

# LabVIEW based measurements and control system of a micro-ORC installation with Scroll Expander

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**Abstract.** An innovative ORC-installation with a scroll engine as expansion device has been developed and designed at the City University of Applied Sciences in Bremen. This new transportable installation has the specific capability to be connected to an alternative power source, such as solar power. Pentafluoropropane (R245fa) has been selected as the working fluid because it is suitable for the required temperature ranges and exhibits some additional advantages related to this specific application. The details of the ORC-Cycle have been presented in another paper and are not the main topic of the presented work. The core matter of this paper is the measurement and control system of the installation, which enables the thermodynamic evaluation of the obtained experimental data, some back coupling, and control tasks. The data acquisition and matching procedure, connected with the operational measurement system, identifies the aggregate and operational states of working fluid in characteristic points of the thermodynamic cycle. The algorithm for searching for the points from the table of parameters take so much time, that the control loop cannot work correctly in time. This problem was solved with the producer-consumer architecture in LabVIEW. Data acquisition and quick response in the control loops are done in the producer-while loop. To reduce the number of values, data are written only every five seconds in a queue. From this queue the consumer-while loop reads values, if the computer has enough capacity. This technique ensures that no data are lost. The matching procedure searches in the parameter file for the thermal properties and displays the cycle in a T-s diagram. Some simple calculation procedures make it possible to evaluate the thermal efficiency and other cycle parameters while operating. At the end of this sequence, the data are saved in a file. In the next step, the producer-loop is executed directly in a Field Programmable Gate Array, so that the control can be executed stand-alone and the computer is only used for visualization.

## 1 Introduction

One of the most effective and efficient modes of energy extraction from previously unsuitable sources is the Organic Rankine Cycle (ORC). Through the ORC, energy from a medium to low temperature (enthalpy) source can be transformed into high-grade energy used for several purposes. Of importance is that energy from a renewable source like wind and solar energy can be converted into high grade energy, which is used for several applications. This system has low maintenance requirements and is highly flexible. Additionally, the system is environmentally friendly because it does not consume any more fuel [1].

The major focus of this paper is the LabVIEW program that was created to analyse, and process the data [2]. The measurement and control system of the installation is the core matter of this paper; it enables thermodynamic evaluation of the data received, back coupling, and control tasks. In short, the LabVIEW program consists of five sections:

- Data acquisition and measurement system
- Control loops for the heating system and the generator

- Matching procedure for the thermal properties of the working fluid
- Thermodynamic evaluation
- Saving results

## 2 Test installation

This ORC-installation is comprised of a scroll expander, a preheater, an evaporator, a condenser, and a feed pump. In order to improve the practical operation, a refrigerant subcooler may be incorporated into the system. This is added after the storage tank and promotes operational quality by ensuring there are no leftover bubbles before the cycle begins again. In Figure 1 below, the ORC-installation with its additional component is shown. To present the full cycle in a T-s-diagram and a h-s-diagram, the temperature and the pressure are measured before (1) and after the expander (2), after the condenser (3), before the subcooler (4), before the feed pump (5), before the preheater (6), and before the evaporator (7). This LabVIEW code was firstly developed within a master project and afterwards improved and optimized continuously in the Laboratory

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for Energetics at Bremen City University of Applied Sciences and is tailored to run tests and change the

parameters while running the micro-ORC installation.

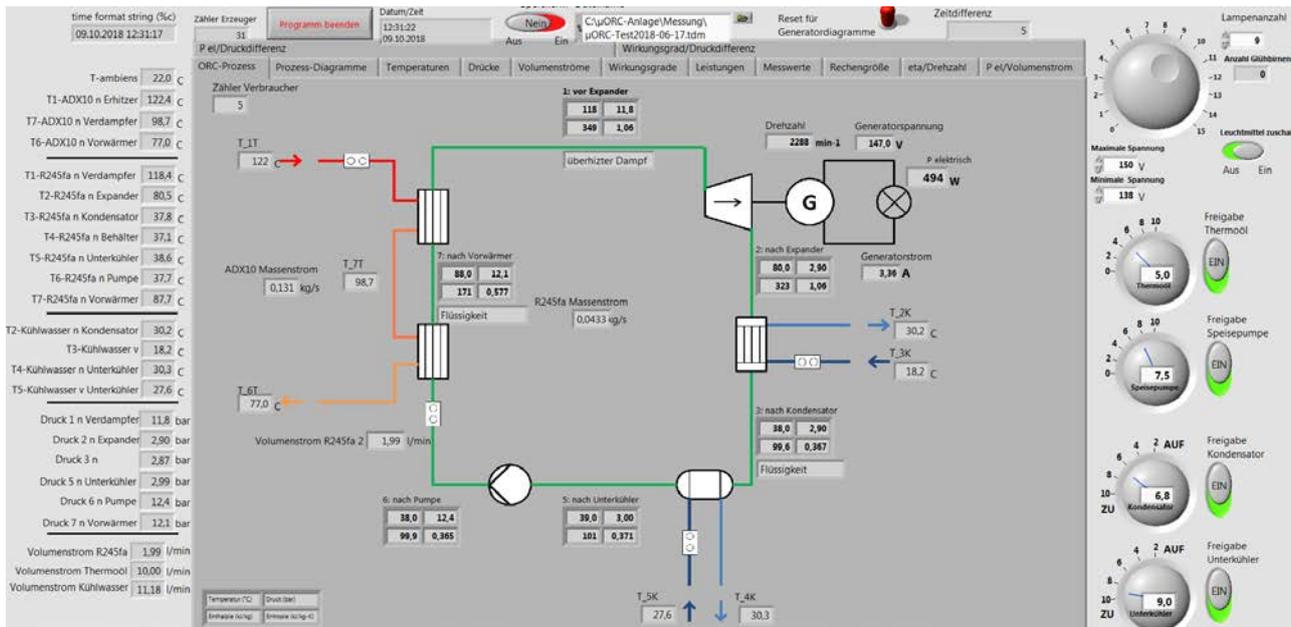


Fig. 1. Micro-ORC LabVIEW Process Diagram Screenshot.

### 3 Producer-Consumer-Problem

In this program, two different tasks are processed; on the one hand a fast data acquisition and quick response in the control loop and on the other hand a lot of calculations which need much calculation time, that the first loop cannot answer in time. To solve this problem, the Producer-Consumer-Architecture in LabVIEW is

used shown in Figure 2. The two tasks are separated in two independent loops. The producer-loop can answer in a certain time and writes only every five seconds the values in queue to reduce the number of values to be shown in the diagram. The consumer-loop reads the values from the queue, as long as the computer has enough capacity to do so. This ensures no data are lost.

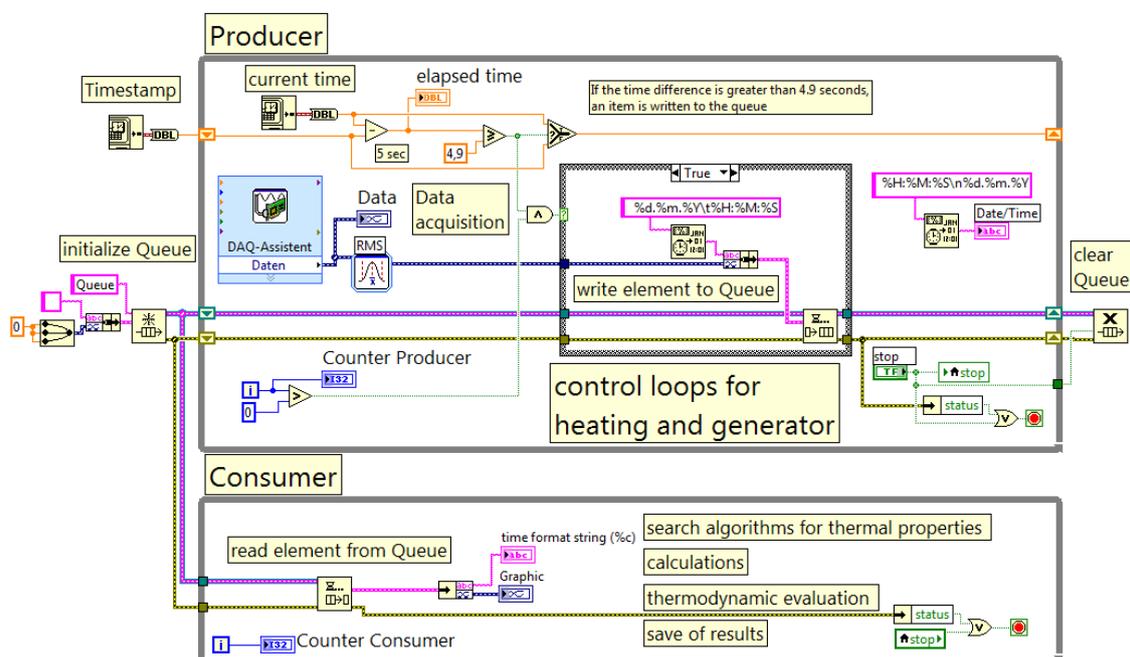


Fig. 2. Producer-Consumer-Architecture with control loops in LabVIEW.

## 4 Producer While-Loop with measurements and control

### 4.1 Data Acquisition of process values

In the producer loop thermal data of temperatures, pressures and volume flow rates of the three cycles are measured. The cycles are thermo-oil heating loop, the refrigerant cycle and the water cooling cycle. Although physical and electrical characteristics like revolution per minute, voltage and current flow are acquired. 500 values are averaged in each second so that the reaction time for the control of the generator and the heating system is pretty short.

Feed pump and circulation pump are adjusted over a frequency conformer by the user. The condenser performance is adjusted over an electric valve but until now not controlled automatically.

### 4.2 Control of the heating system with Pulse Width Modulation

This process had to be adopted to control heating power. The temperature  $t_1$  at the input of the expander should be held constant. If the fluid is a few degrees superheated it makes it easier to control the whole cycle and to reach and keep a steady state. The LabVIEW program is able to accomplish this through Pulse Width Modulation. A Mechanical Switch Relay is employed, and the time duration after each step is chosen to 50 seconds, which results in a temperature difference of 3 K. This time was chosen so long, so as not to endanger the mechanical switch by too high switching cycles. The original built in two-point switch causes a temperature difference of 30 K. In the future, a shorter time between each step would reduce the difference of temperatures in the refrigerant. However, too short a step-time would melt the switch. To realize this reduced step-time in future, a solid-state relay could be employed. With this change, the time period between each switch could be, for example, one second instead of the current 50 seconds.

### 4.3 Control of the load of the generator

Generator control refers to the ability to set the voltages to control the generator. In the case that less energy than required comes from the expander, the load from the generator would have to be lowered to maintain the speed of the generator and expander. The voltage and speed of the scroll engine are set by the user, for example, within a range of 138  $V_{min}$  to 150  $V_{max}$ . The control loop would set one lightbulb to either turn on or off to maintain the speed of both the generator and scroll engine.

## 5 Consumer While-Loop with calculations

In this loop, the calculations are done to prepare the visualisation and evaluation of the cycle. To calculate the latent heat of vaporisation it is necessary to determine the enthalpy and the entropy of the characteristic points of the process. To make the main program clearer, the matching procedure and some calculations are done in a sub-program. Finally, the results are saved every ten seconds. In LabVIEW these virtual instruments are called sub-VI.

### 5.1 Matching procedure for the thermal properties of the working fluid

One sub-VI searches in a table of thermal properties for enthalpy and entropy with the input of temperature and pressure. At first, it is checked if the measured values are in the array from 0.12 MPa to 1.4 MPa and from 20 °C to 140 °C as shown in Table 1. The table was created with the program Genetron Properties V1.3 from the company Honeywell based on the data from the National Institute of Standards and Technology (NIST) Refprop 9.1 ASHRAE [2]. The values are grouped by a temperature from 20 °C in increment of 1 °C to 140 °C and constant pressure. The pressure is then increased by 0.01 MPa and the next group is attached. The maximum pressure is set to 1.4 MPa.

**Table 1.** Thermal properties for R245fa from 0.12 MPa to 1.4 MPa and from 20 °C to 140 °C.

	temperature	pressure	density	enthalpy	entropy	specific heat
No.	t	p	$\rho$	h	s	$c_p$
	°C	MPa	kg/m <sup>3</sup>	kJ/kg	kJ/(kg*K)	kJ/(kg*K)
0	20.0	0.12	6.98	268.99	0.9488	0.9338
1	21.0	0.12	6.95	268.92	0.9520	0.9335
..	..	..	..	..	..	..
15123	139.0	1.40	65.81	370.76	1.1021	1.2222
15124	140.0	1.40	65.49	371.98	1.1050	1.2206

This array is separated into two tables: one for temperature and one for pressure. The row numbers which correspond with the searched temperature and the searched pressure are each written in an array. In the second step, the row numbers are checked that they are

equal. The values for density, enthalpy, entropy, and specific heat of this found out row are given back to the main program. This is done for all the points described above until the point 4 in the storage tank where no phase change occurs.

Especially the points of evaporation and condensation, the saturated states, are very interesting for the evaluation of the cycle. A second sub-VI searches in this case in table 2 with the properties of the saturation line

also with the input of temperature and pressure for enthalpy and entropy. But in this case the table includes both, saturated liquid point, marked with h' or s', and the saturated vapour point, marked with h'' or s''.

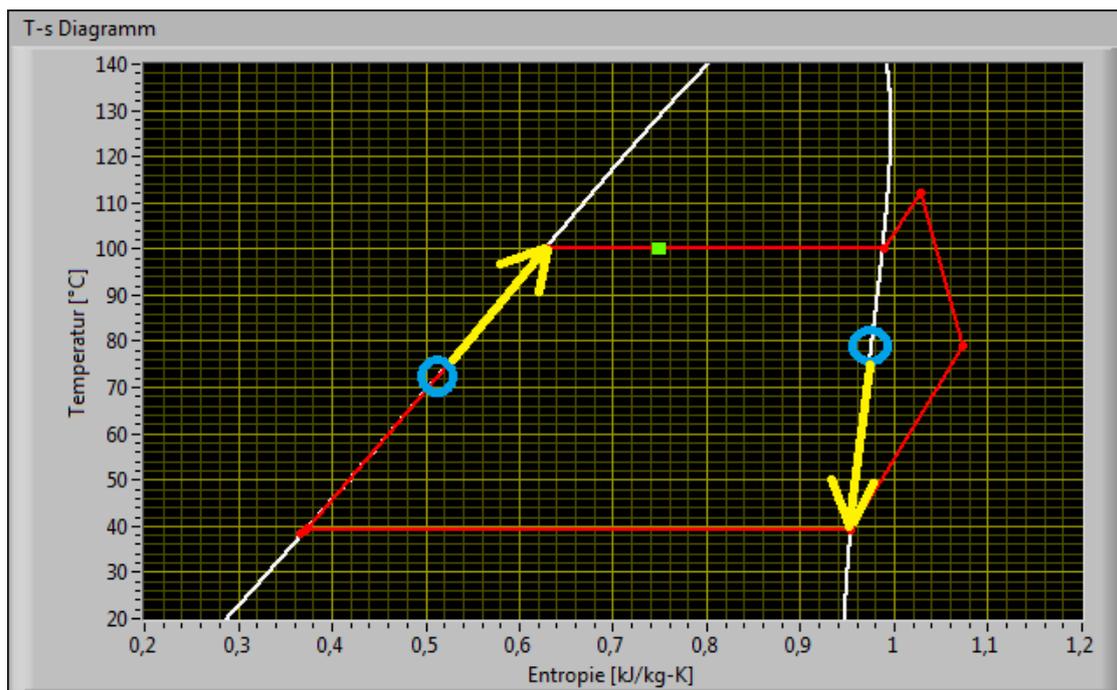
**Table 2.** Saturation curve for R245fa from 0 °C (0.0 MPa) to 146.8 °C (3.2 MPa).

No.	temperature	pressure	density'	density''	enthalpy'	enthalpy''	entropy'	entropy''
	t	p	$\rho$	$\rho$	h'	h''	s	s
	°C	MPa	kg/m <sup>3</sup>	kg/m <sup>3</sup>	kJ/kg	kJ/kg	kJ/(kg*K)	kJ/(kg*K)
0	0.0	0.053	1403.97	3.23	49.76	254.22	1.1967	0.9453
1	0.1	0.053	1403.72	3.24	49.88	254.30	1.1972	0.9453
..	..	..	..	..	..	..	..	..
1467	146.7	3.198	795.26	264.52	274.48	335.98	0.8361	0.9826
1468	146.8	3.203	793.96	265.62	274.73	335.91	0.8366	0.9823

This sub VI selects the pressure of saturation for the measured temperature from this table and compares it with the measured pressure. If the values are equal within the measurement accuracy, the condition point is in the wet steam area.

If the pressure value from table 2 for the measured temperature is higher than the pressure, then the steam was superheated. To find the correct point on the evaporation line, the pressure for a lower temperature in the row above is compared with the measured pressure iteratively until this difference is zero - see the right side on figure 3.

In the third case, if the pressure value from table 2 for the measured temperature is lower than the pressure, the fluid was in a liquid area. Now the pressure corresponding with a higher temperature in the row underneath is compared with the measured pressure iteratively until this difference is zero. In all three cases both values for enthalpy and entropy are returned to the main program and can be used for the visualisation and further calculations.



**Fig. 3.** T-s-diagram with the Organic-Rankine-Cycle finding the saturation points.

### 5.2 Thermodynamic calculations of energy balance

In the heat exchanger, it is possible to calculate the balance of the heat flow between the thermo-oil heating cycle and the cycle of the working fluid to determine the

energy input of the ORC-installation, shown in Figure 1. In the thermo-oil section of the plate heat exchanger the heat flow is calculated by the multiplication of the mass flow rate, the specific heat capacity and the temperature difference between input and output. In the working fluid, a phase change is expected to occur, so that the calculation here must be done with enthalpies. In the

refrigerant section of the heat exchanger, the heat flow is calculated by the multiplication of mass flow rate and enthalpy difference between inlet and outlet. With this knowledge it is possible to calculate the vapour mass fraction.

### 5.3 Calculation of the vapour mass fraction

The refrigerant heating takes place in two steps. A preheater increases the temperature from 40°C to 104°C. The second heat exchanger evaporates the fluid and superheats it to 115°C at a pressure of 1.1 MPa. An additional challenge is the determination of the aggregate state between the preheater and the evaporator. In order to visualise this state a sight glass was installed at this point. For quantitative determination of the relevant state the vapour mass fraction should be computed.

In a T-s-diagram shown in Figure 4 the area under the curve of a cycle can be expressed as a heat flow. Now the heat flow calculated in the heat exchanger by readings is compared with the area in the diagram. In an additional sub-VI the area of the heat from 40°C to

104°C (approximately a triangle) and the evaporation (a rectangle) are summed up in small steps and multiplied with the mass flow iteratively until this calculated heat power is equal to the power transferred in the preheater. The same calculation is done for the evaporator. But in this case, the calculation starts at the state point t1 with the triangular area of superheating and adds the rectangle area of evaporation from right to left until the heat flow is balanced. So the entropy for this state point is computed on to different ways. Now the mass fraction can be calculated by dividing this value by the entropy difference for the latent heat.

The increment of the entropy in the range of evaporation is 0.005 kJ/(kg\*K). In the integral calculus for preheating, values from the saturation line (table 2) are used. The integral for superheating is based on the thermal properties from table 1 so that the step width is given from these tables. These triangle areas are approximated with many small rectangle areas which are always lower than the correct value, but because of the accurate tables, the differences are small.

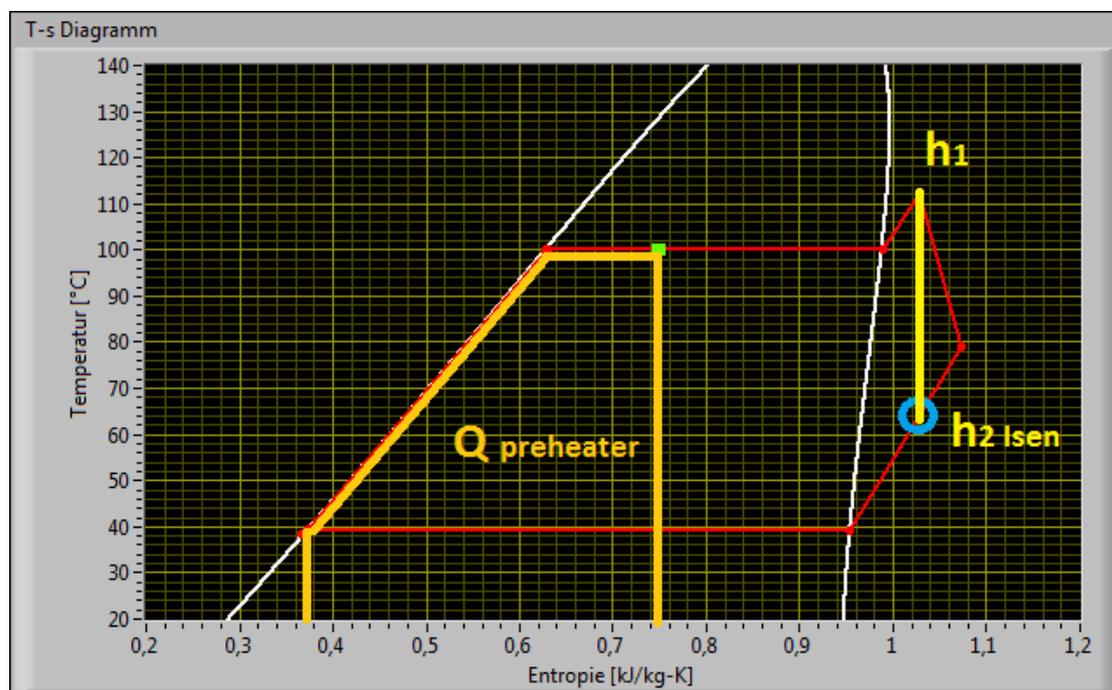


Fig. 4. T-s-diagram determines vapour mass fraction and thermal efficiency.

### 5.4 Performance and efficiency

The internal thermal efficiency of the expander is calculated by the real difference of the enthalpy divided by the difference of the enthalpy in isentropic expansion (see Figure 4). This requires the knowledge of the enthalpy  $h_{2\text{isentropic}}$  at the output if an isentropic expansion occurs.

Here, nearly the same sub-VI, described above, is used for searching the state point. The database is again the thermal properties from table 1. However, in this case, the inputs are the pressure  $p_2$  at the end of the expansion and instead of the temperature the entropy  $s_1$  at the

beginning of the expansion. The uncertainty for the searching procedure for the entropy is  $\pm 0.0023$  kJ/(kg\*K). The row numbers which matched the searched entropy and the searched pressure are compared. If the row numbers are equal, it is returned to the main program. Now the internal efficiency of the expansion machine can be calculated.

In addition, it is also possible to calculate and visualise the general energy balance, the energy losses, the overall efficiency between the heat input of the thermo-oil into the system and the electric power of the generator.

## 6 Conclusions and prospects

A producer-consumer-architecture with queuing data makes it possible to run the control-loop very quickly but also gives the possibility to search for every relevant point of the refrigerant cycle in a huge parameter file of 15125 values.

The sensitivity analysis shows that the increment of 0.01 MPa is too accurate. The control of heating section can be improved through a solid-state relay, which would reduce the time between each step of the Pulse Width Modulation. Improvement in the producer-loop section can be achieved through its execution in a Field Programmable Gate Array, so that the control can be executed stand-alone and the computer will be used only for visualization.

## References

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